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ADVANCED TRAJECTORY OPTIONS FOR THE EXPLORATION OF THE PLUTO-CHARON SYSTEM

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Abstract

In this paper some new advanced trajectory options for a mission to Pluto have been investigated. In particular low-thrust gravity assist trajectories based on a nuclear electric propulsion system (powered by RTGs) have been analysed, demonstrating how a substantial payload could be inserted into a low altitude stable orbit around Pluto. The stability of this orbit has been analysed in order to achieve a lifetime sufficient for a complete mapping of the planet. The interplanetary trajectories have been designed using an innovative global optimisation technique for first guess generation followed by a fine optimisation of the obtained first guess using DFET and nonlinear programming.

1. Introduction

At present the only approved mission to Pluto[1] proposes to carry out a very quick flyby of Pluto and Charon with a large relative velocity. Although the probe will be operative months prior to the encounter with the distant plant the scientific return will be limited by the high excess velocity. The foreseen mission to the outer part of the solar system will then proceed heading toward the Kupier belt targeting one of the still unknown bodies present in that region.

If the interest of the mission is focused on Pluto and Charon (the natural satellite of Pluto), the scientific return would increase tremendously if either the fly-by would occur at a small relative velocity or if the spacecraft could go into orbit around the Pluto-Charon system.

From a technological point of view, inserting a probe in orbit around such a distant planet at a reasonable propellant expenditure, and with a limited transfer time, poses considerable issues both in terms of propulsion and power. Recent studies[2,3] showed the potentialities of using radioisotope electric propulsion for missions to distant planets. In particular it was considered[3] the possibility of sending a small probe to Pluto using nuclear electric propulsion (NEP), via a swing-by of Jupiter showing how this advanced technology could allow the insertion of some 400 kg into a highly elliptical orbit around the distant planet provided a very low thrust propulsion system (about 0.038 N) powered by a cluster of four RTGs.

This option is however just one of the possible options for a transfer to Pluto and despite the swingby of Jupiter still requires a considerable C_3 at launch and a launcher completely dedicated to this mission. In order to reduce the overall cost of the mission, different transfer options can be considered exploiting multiple swinby sequences. Furthermore the lifetime of the spacecraft and the actual operability of the payload while in orbit around Pluto were not addressed in the previous analysis.

Therefore, in this paper, additional transfer options have been analysed including both direct launches to Jupiter to exploit its gravity pull and indirect transfers exploiting a sequence of swingbys of Venus and Earth to reduce the demands in terms of launch C_3.

In addition the final orbit around Pluto has been selected after an analysis of its stability in view of a complete mapping of the surface of Pluto. The dynamics of the probe is modeled considering the principal attraction of Pluto perturbed by the presence of Charon and by the gravity pull of the Sun.

The design of the NEP trajectories has been performed with a direct transcription method by finite elements in time[5] (DFET). However the problem presents quite a number of possible solutions dependent on launch window, transfer time and combination of planetary encounters, therefore in order to find favorable launch windows and the optimal sequence of swing-bys a global optimization strategy[4] has been used to procure sets of promising initial guesses.

This global algorithm blends together some of the main features of systematic techniques such as branching and cut and interval analysis with the characteristics of

heuristic or stochastic methods such as evolution programming (EP).The particular combination of both and the special implantation of evolution programming employed in this work are used to perform an exhaustive exploration of the solution space in search for several optimal solutions and eventually for the global one.
Then, these initial guesses have been optimised using direct transcription and NLP.

2. Mission Analysis

2.1 First Guess Generation

The aim is to find an optimal sequence of transfers from the Earth to Pluto passing by a predefined number of intermediate swingbys. Even though the propulsion system is electric and not chemical, the trajectory, which minimizes the overall cost in terms of Δv corrections for each gravity assist manoeuvre, is taken as an optimal first guess solution suitable for a further optimisation with electric propulsion. This latter optimisation has been performed using DITAN[5] (a software tool for the design of gravity assist low-thrust trajectories, developed by Politecnico di Milano under ESA contract).
Therefore for a first guess generation, initial conditions at the Earth, given in terms of ephemeris of the Earth and initial Δv_0 modulus and angle α, are analytically propagated forward in time considering a 2-body dynamics. If an intersection with the orbit of another planet occurs, a gravity assist manoeuvre is performed using a linked conic model. The swingby is modelled with an instantaneous impulsive rotation of the velocity vector relative to the encountered planet.
The incoming relative velocity $\tilde{\mathbf{v}}_i$ obtained from the intersection of the propagated arc with the orbit of the encountered planet, is rotated of and angle δ, function of the periapsis radius $\tilde{r}_p$:

$$\delta = \pi - 2a\cos\left(\frac{\mu}{\tilde{v}_i^2 \tilde{r}_p + \mu}\right) \qquad (1)$$

with μ the gravity constant of the planet. The resulting rotated outgoing velocity vector $\tilde{\mathbf{v}}_o$ is:

$$\tilde{\mathbf{v}}_o = \mathbf{Q}(\mathbf{n}_\delta)\tilde{\mathbf{v}}_i \qquad (2)$$

With $\mathbf{n}_\delta$ the normal to the swingby plane. The rotation matrix **Q** is defined by the quaternions:

$$\mathbf{q} = \left[\mathbf{n}_\delta \sin\frac{\delta}{2}, \cos\frac{\delta}{2}\right] \qquad (3)$$

The initial conditions given by the outgoing velocity vector and by the position of the intersection, are propagated further to the next intersection with the next desired planetary orbit.
If the model is 2D, as in this work, the swingby plane is the ecliptic plane and all the trajectories are therefore contained in the ecliptic plane. Thus, starting from the Earth it is possible to reach another desired planet passing by a number of swingbys and providing an initial Δv_0 manoeuvre. The launch date is then modified to match the intersection between the propagated trajectory and the orbit of the planet with the actual position of the planet. In Pessina et al.[7] the described approach was used for systematic search for multipleGA or multipleAGA trajectories to distant targets with good results.
Instead of using a systematic scanning of all possible transfer, here the search for minimum Δv transfers to Pluto is formulated as a general nonlinear global optimisation problem that can be written in the following form:

$$\min_{\mathbf{y}\in D} f(\mathbf{y}) = \begin{cases} \sum_{j=1}^{M} \mathit{\Delta} R_j \;\; if \;\; M \neq 0 \\ \Delta v_0 + \sum_{i=1}^{N} \Delta_i \; if \;\; M = 0 \end{cases} \qquad (4)$$

where N is the number of planetary encounters, Δ_i is the i-th angular miss distance in radiant, or the angular difference between the intersection point and the actual position of the planet and M is the number of missed intersections.
For every missed intersection *j,* the difference of the planet mean distance from the Sun and the apocentre radius (if going outward) or the pericentre radius (if going inward), for the transfer orbit is computed.
Then *D* is the search space and the solution vector **y** is:

$$\mathbf{y} = [p_1,..., p_i,..., p_N, t_0, \Delta v_0, \alpha, h_1,..., h_i,..., h_N]^T \qquad (5)$$

where p_i represents the i-th planet's identification number, t_0 is the departure date and h_i. is the i-th swingby altitude.
The problem of designing a trajectory visiting more than one planet on its way to Pluto, defined by Eq. (6), can now be solved looking for the sequence and the date of the encounters that minimise the objective *f*.
This is a mixed inter-nonliner programming problem with multiple solutions and a discontinuous objective function. Due to its nature, it can not be solved by a local optimizer based on gradient methods like common NLP solvers used in direct collocation and a global technique should be used instead. The global search of the solution space

has been carried out using a mixed systematic-stochastic method, combining branching technique[4] and evolution programming to explore the subintervals or subdomains derived from the branching step.

The most interesting preliminary solutions found by the global search have been optimised using DITAN.

In particular two possible strategies have been investigated: a direct launch to Jupiter and a multiple swingby trajectory visiting more than one internal planet before the transfer to Jupiter.

In the former case the search space is defined by the boundaries in Table 1, while in the later case the search space is defined by the values in Table 2.

Table 1 Search Space for the EJP strategy

p_1	p_2	t_0	Δv_0	α	h_1
5	9	5000	9	0	1e5
5	9	7000	12	π	1e7

Table 2 Search Space for the EVVEJP strategy

p_1	2	2
p_2	1	4
p_3	1	4
p_4	4	6
p_5	9	9
t_0	5000	10000
Δv_0	3	5
α	$-\pi$	0
h_1	300	1e5
h_2	300	1e5
h_3	300	1e5
h_4	1e5	1e7

Table 3. Summary of EJ-Pluto Option 1

Planet	Date	h_p (km)	v_∞ (km/s)
Earth	20/12/2016	/	10.755
Jupiter	21/04/2018	7.6e5	13.27
Pluto	15/01/2021	/	15.19

Table 4. Summary of EJ-Pluto Option 2

Planet	Date	h_p (km)	v_∞ (km/s)
Earth	27/01/2018	/	12.859
Jupiter	12/01/2019	1.3e6	18.17
Pluto	09/07/2020	/	17.5

Exploring the search space defined in Table 1 gives rapidly a considerable number of solutions with different levels of initial departure Δv. The ones selected for this study are a launch opportunity in 2016 and a backup option in 2018. The two solutions, reported in Table 3 and 4 have very short transfer time to Pluto but with a considerably high swingy velocity. The reduced orbit model used here yields a good matching of the actual position of Jupiter but a relevant error for Pluto. Of course since a 2D model is employed a significant error in inclination is expected.

A second set of solutions have been computed after a longer exploration of the search space defined in Table 2. In this case the sequence is partially free. The most interesting option found is an EVVEJP transfer in 2013 with a 1:1 resonant swingby of Venus.

In this case the transfer time is considerable longer but the improvement in initial Δv is very interesting.

The number of used swingbys reduces the number of launch opportunities therefore a possible backup option could be found in 2024.

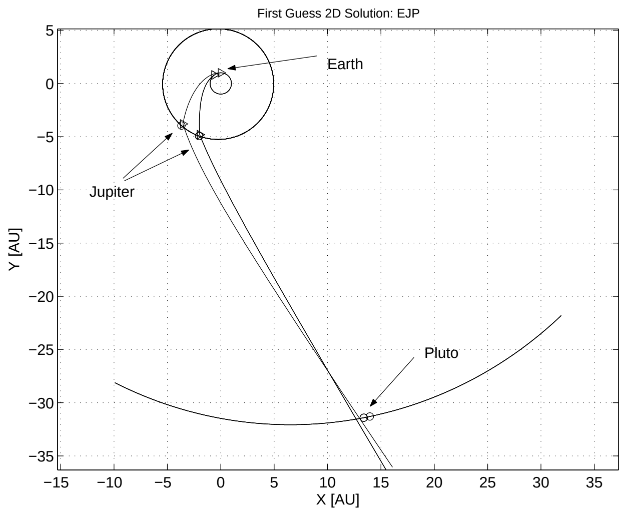

Figure 1. First guesses for EJ-Pluto Transfers

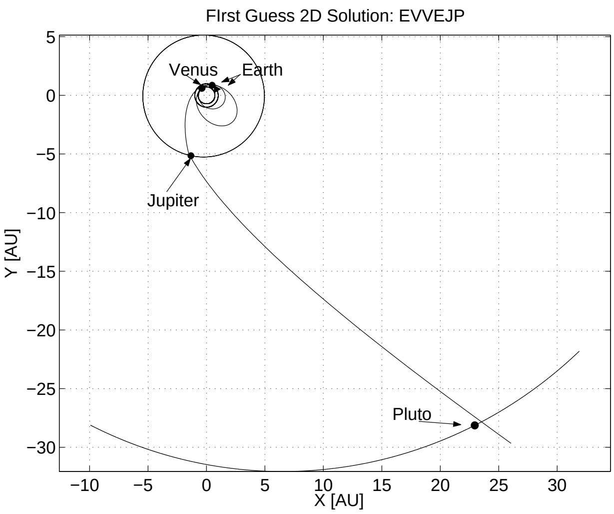

Figure 2. First guess for the EVVEJP Transfer

Table 5. First guess for the EVVEJP Transfer

Planet	Date	h_p (km)	V_∞ (km/s)
Earth	24/10/2013	/	4.799
Venus	19/01/2014	2398.3	10.41
Venus	11/04/2015	306.1	10.41
Earth	22/11/2017	896.8	17.01
Jupiter	20/04/2019	2.195e6	13.31
Pluto	20/01/2030	1e6	8.167

Table 6. Backup First guess for the EVVEJP Transfer

Planet	Date	h_p (km)	v_∞ (km/s)
Earth	09/10/2024	/	4.385
Venus	13/09/2025	3969.0	8.918
Venus	07/12/2026	3858.6	8.918
Earth	28/10/2028	946.07	15.251
Jupiter	09/07/2030	8.047e5	9.928
Pluto	21/09/2035	/	11.175

Notice that the reduced model does not allow for free complete revolutions around the Sun between two subsequent encounters. Although these free revolutions may increase the transfer time on the other hand they can increase also the number of launch opportunities, a problem that has not been addressed here.

2.2 Low Thrust Transfers

Once a suitable set of first guesses had been obtained the most interesting ones were fully optimised with a complete 3D model and low-thrust propulsion.

A parallel and concurrent pre-feasibility study at system level for mission named POP (Pluto Orbiter Probe) yielded the characteristics of the spacecraft summarised in Table 7.

Table.7. Main characteristics of the spacecraft at BOL

POWER SOURCE	THRUST (N)	I_{SP} (s)	MASS (kg)
RTG	0.036	4500	830

The first guess solution of Tab. 3,4 and 5 have been fully optimised constraining the C_3. For the two EJP options the C_3 was constrained down to 100 km^2/s^2, in order to meet the capabilities of the future Ariane 5 initiative 2010. The resulting solutions have been plot in Fig.3 and the main feature have been summarised in Tab.8 and 9. For the EVVEJP option the C_3 has been constrained to be lower than 25 km^2/s^2 to meet the capabilities of a cheaper launcher as the Soyuz with Fregat upper-stage. The resulting solution has been plot in Figs. 4 and 5 and summarised in Tab 10 (in all the figures only the relevant planets have been inserted for clarity).. For all three options, the final mass of the spacecraft has been optimised fixing and upper limit on the Jupiter-Pluto transfer time of 5500 days.

The arrival velocity at the sphere of influence and the first pericentre have been determined considering a spiral up from the required final target orbit (see Table 12) with constant thrust up to the limit of the sphere of influence. The reported final mass for the three cases is inclusive of the propellant required to achieve the final orbit.

If then the arrival velocity at the sphere of influence is reduced down to 200 m/s for an increased safety capture the final mass for option 1 reduces down to 625 kg.

Table 8. Summary of EJ-Pluto Option 1 with NEP

Planet	Date	h_p (km)	v_∞ (km/s)
Earth	21/11/2016	/	10
Jupiter	07/08/2018	2.52e7	12.71
Pluto	28/04/2036	1e6	0.60
Final Mass	638.5 kg		

Table 9. Summary of EJ-Pluto Option 2 with NEP

Planet	Date	h_p (km)	v_∞ (km/s)
Earth	17/01/2018	/	10
Jupiter	31/05/2019	1.274e6	14.38
Pluto	21/06/2034	1.16e5	0.62
Final Mass	615 kg		

Table 10. Summary of EVVEJ-Pluto Transfer with NEP

Planet	Date	h_p (km)	v_∞ (km/s)
Earth	20/09/2013	/	5
Venus	05/02/2014	2144.47	6.72
Venus	11/04/2015	300	10.68
Earth	24/11/2017	300	16.92
Jupiter	28/04/2019	1.1e6	14.20
Pluto	19/05/2034	1.16e5	0.62
Final Mass	623.5 kg		

Table 11. Capture Orbit

Parameter	EJP Option 1	EJP Option 2	EVVEJP
a	-2576.3 km	-2454.4 km	-2454.5km
e	47.03	49.31	48.34
i	99°	99°	99°
Ω	127°	127°	127°

Table 12. Final Orbit

Parameter	Value
a	2150 km
e	0.001
i	99°
Ω	127°

Although the final mass for option EVVEJP is about 15 kg lower than for option EJP, the required C_3 is considerably lower allowing for either a larger payload mass in orbit or for a cheaper launch. The total transfer time for this last case is 5 years longer than for the direct EJP transfer in particular due to the last Venus-Earth transfer after the 1:1 resonant Venus-Venus transfer.

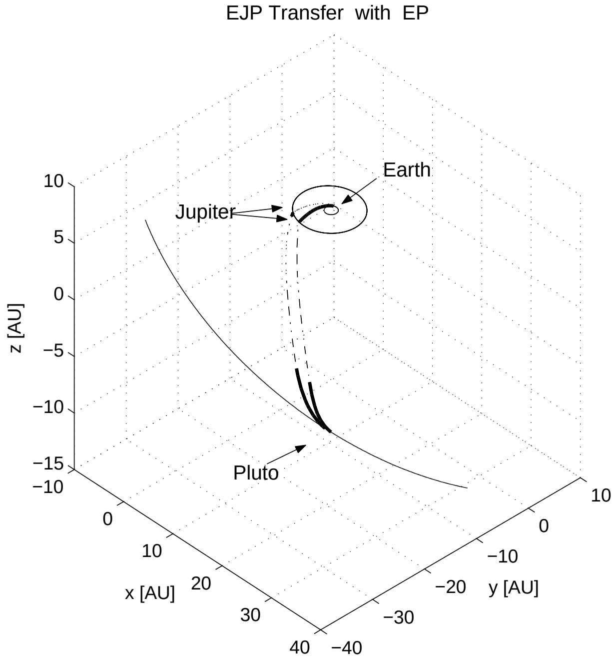

Figure 3. Optimised EJP solutions with NEP: solid lines are thrust arcs, dotted lines are coast arcs.

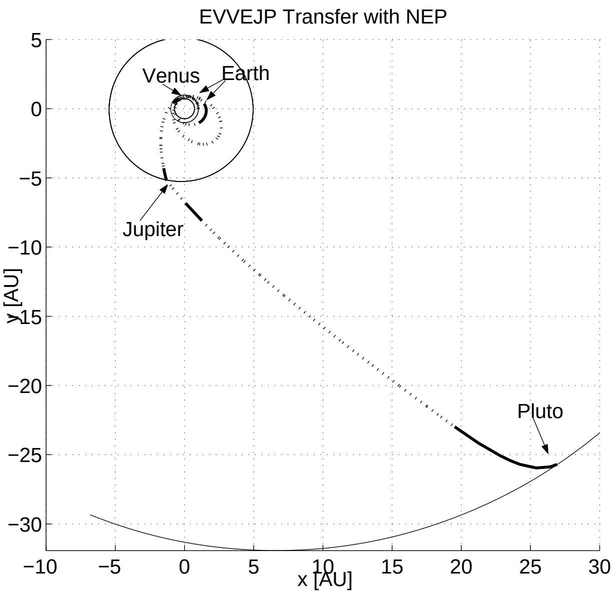

Figure 4. Optimised EVVEJP solution with NEP: xy plane. Solid lines are thrust arcs, dotted lines are coast arcs.

The contribution of Jupiter in all three cases is not just to accelerate the spacecraft toward Pluto but also to rotate partially the orbit plane from the ecliptic to about 6° for EJP option 1 and to about 9° for the other two options (as can be seen in Fig. 6). The final burn produces an additional turn up to 16.8° and the required brake to meet capture conditions at Pluto.

Notice how, despite the two propulsion systems employed for first guess generation and for the final optimization are completely different, first guesses and final optimal solutions are in good agreement for what the launch dates and swingby dates are concerned.

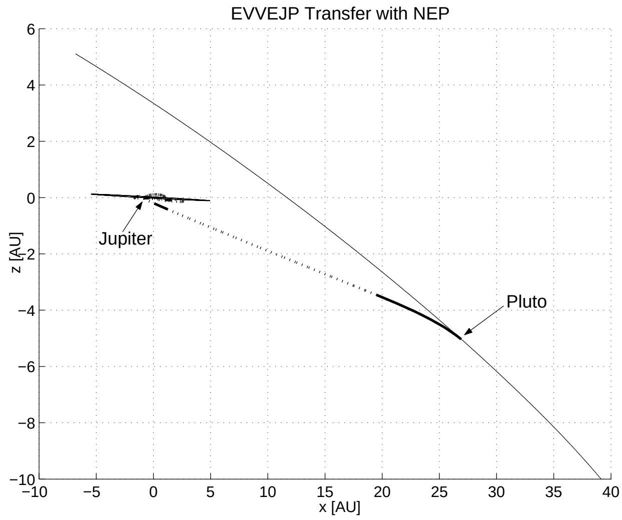

Figure 5. Optimised EVVEJP solution with NEP: xz plane. Solid lines are thrust arcs, dotted lines are coast arcs.

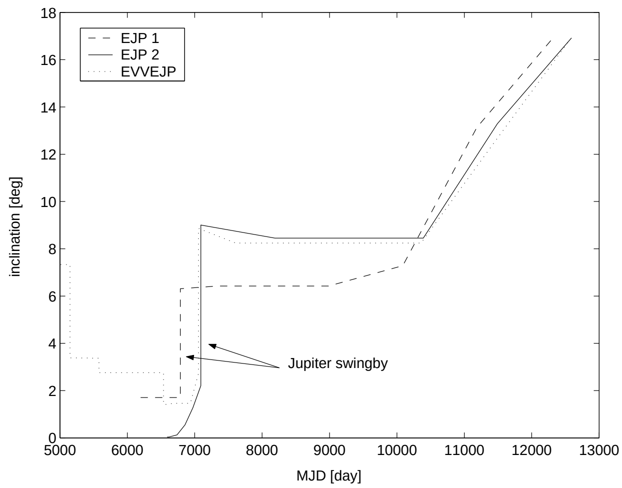

Figure 6. Inclination time history for the three transfers.

2.3 Orbit Stability Analysis

Since Charon is considerably massive compared to Pluto the dynamics of a spacecraft orbiting the planet at low altitude can be significantly influenced by the gravity disturbance of Charon and the orbital parameters can be subject to large variations leading to either a crash into Pluto or into Charon.

On the other hand a high altitude orbit, ideal for a low

cost capture, is influenced by the gravity perturbations of the Sun.
Therefore the choice of the final orbit around Pluto has been made analysing the lifetime of the orbit as a function the starting orbital parameters.
Two gravity perturbations due to: the Sun and to Charon. have been inserted in the dynamics considering analytical ephemeris for both celestial bodies. Initial orbital parameters have been then propagated forward in time until a crash either into Pluto or into Charon occured.

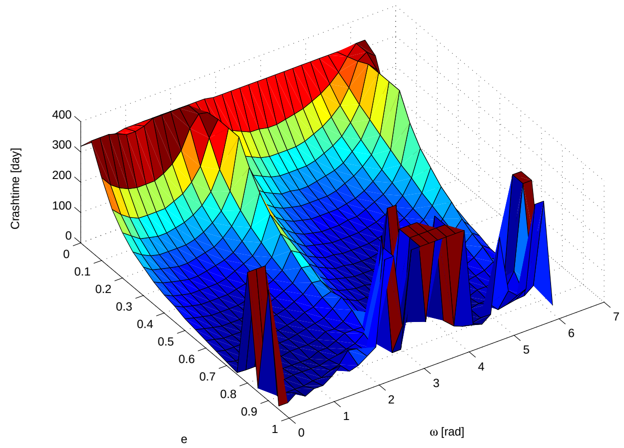

Figure 7. Lifetime as a function of e and ω

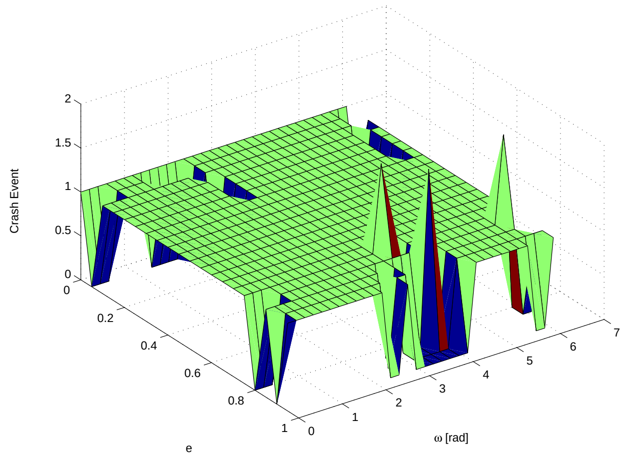

Figure 8. Crash events: 1 crash with Pluto, 2 crash with Charon

For scientific reasons the preferred orbit would be almost polar therefore the orbit stability was analysed for polar orbits with variable eccentricity and a fixed pericentre at 2150km and with variable pericentre anomaly ω.
The result can be read in Figures 7 and 8 respectively for the lifetime of the orbit (in days) and for the crash event, i.e. a value of 1 corresponds to a crash in Pluto a value of 2 corresponds to a crash into Charon and 0 means no crash. As can be seen circular or almost circular orbits (as the one selected) are stable enough for the time required for the mission.

3. Conclusion

In this work an investigation of advanced trajectory options for a probe aiming at orbiting Pluto has been performed. Some interesting opportunities have been found with a global exploration of the solution space for multiple swingby transfers. The most promising solutions have been optimised considering NEP as primary propulsion. The presented results demonstrated the possibility to insert a small probe (about 600kg of dry mass) into a stable low altitude orbit around Pluto. This can be achieved either with a fast transfer via Jupiter or with a cheap launch with a reduced C_3 of 25 km^2/s^2.

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